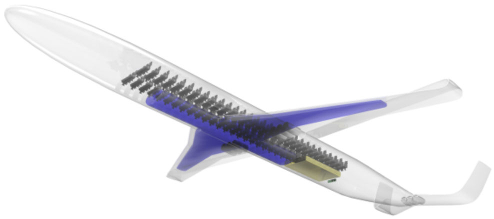

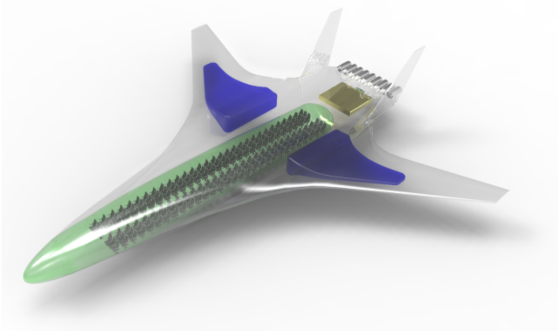

Enabling Carbon-Free Commercial Aviation Through Integrated, High-Fidelity Conceptual Design

NASA Aeronautics Research Mission Directorate (ARMD)
FY 2012 LEARN Phase I Technical Seminar
November 15, 2013

Juan J. Alonso, Michael R. Colonno

STANFORD AERONAUTICS & ASTRONAUTICS
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Outline

- ✓ Main Innovation: High-fidelity Conceptual Design of "N+X" Aircraft with electric propulsion concepts
- ✓ Technical Approach: SUave and ADL Tools
- ✓ Technical Impacts:
  - ✓ Open-source Vehicle Design Software Tools
  - ✓ Carbon-free Aircraft Concepts
- ✓ Summary of LEARN Phase I efforts
- ✓ Distribution & Dissemination
- ✓ Future Work & Phase II Foci

Acknowledgements

- ✓ A team of students at Stanford University has participated in this effort: (Trent Lukaczyk, Anil Variyar, Jeff Sinsay, Andrew Wendorff, Michael Vegh, Tom Economon, and others)

- ✓ IBM *Battery 500* Program: (Winfried Wilcke)

- ✓ NASA: (Mark D. Guynn)

- ✓ American Superconductor: (Bruce Gamble and Glenn Driscoll)

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Innovation & Motivation

- ✓ Commercial aviation is ~ 7th largest country in the world measured by greenhouse gas emissions
- ✓ Commercial air travel is expected to double by 2025 (baseline 2005)
- ✓ Incremental improvements in hydrocarbon-fueled aircraft cannot meet the climate change demand
- ✓ In order to reduce greenhouse emissions to acceptable levels, **fundamental** change is needed in commercial fleet
- ✓ This requires radically-new aircraft with "clean sheet" power and propulsion system designs
- ✓ This, in turn, requires a new way of designing aircraft that is not based on traditional techniques and/or historical correlations

Technical Approach

- ✓ **SUave**: Stanford University Aerospace Vehicle Environment
- ✓ A central hub for conceptual design for aerospace vehicles
  - Flexible, extensible, easy-to-use environment for mission analysis
  - No explicit dependence on traditional sizing / analysis methods
  - Incorporates arbitrary levels of fidelity in analysis and geometry
  - Communicate with existing geometry tools, including OpenVSP, CAD, etc.
- ✓ Completely flexible power & propulsion network, supporting any combination of electrical, chemical, or other systems
- ✓ Communicates semi-automatically with ADL's CFD / shape optimization suite, SU^2 (su2.stanford.edu)
- ✓ Acts as an API (Python) which can be driven from any optimizer (e.g. OpenMDAO) or design suite

Technical Approach

- ✓ **SUave** works in a scripted, object-oriented way with "plain English" syntax: `a_wing = SUAVE.Components.Wing()`
- ✓ **Vehicles** are constructed by adding **Components** of many types (Wings, Bodies, Propulsors, Energy Storage, etc.)
- ✓ **Missions** are constructed in a similar fashion by adding **Segments** (Cruise, Climb, Descent, Glide, even Orbit)
- ✓ Vehicles and Missions are kept strictly independent:
  - A given Vehicle can be run through numerous Missions
  - Numerous Vehicles can be run through a given Mission
  - An array of Vehicles / Missions can easily be looped over
- ✓ Valid solution found even for infeasible Vehicle / Mission combinations (built with optimization support in mind)

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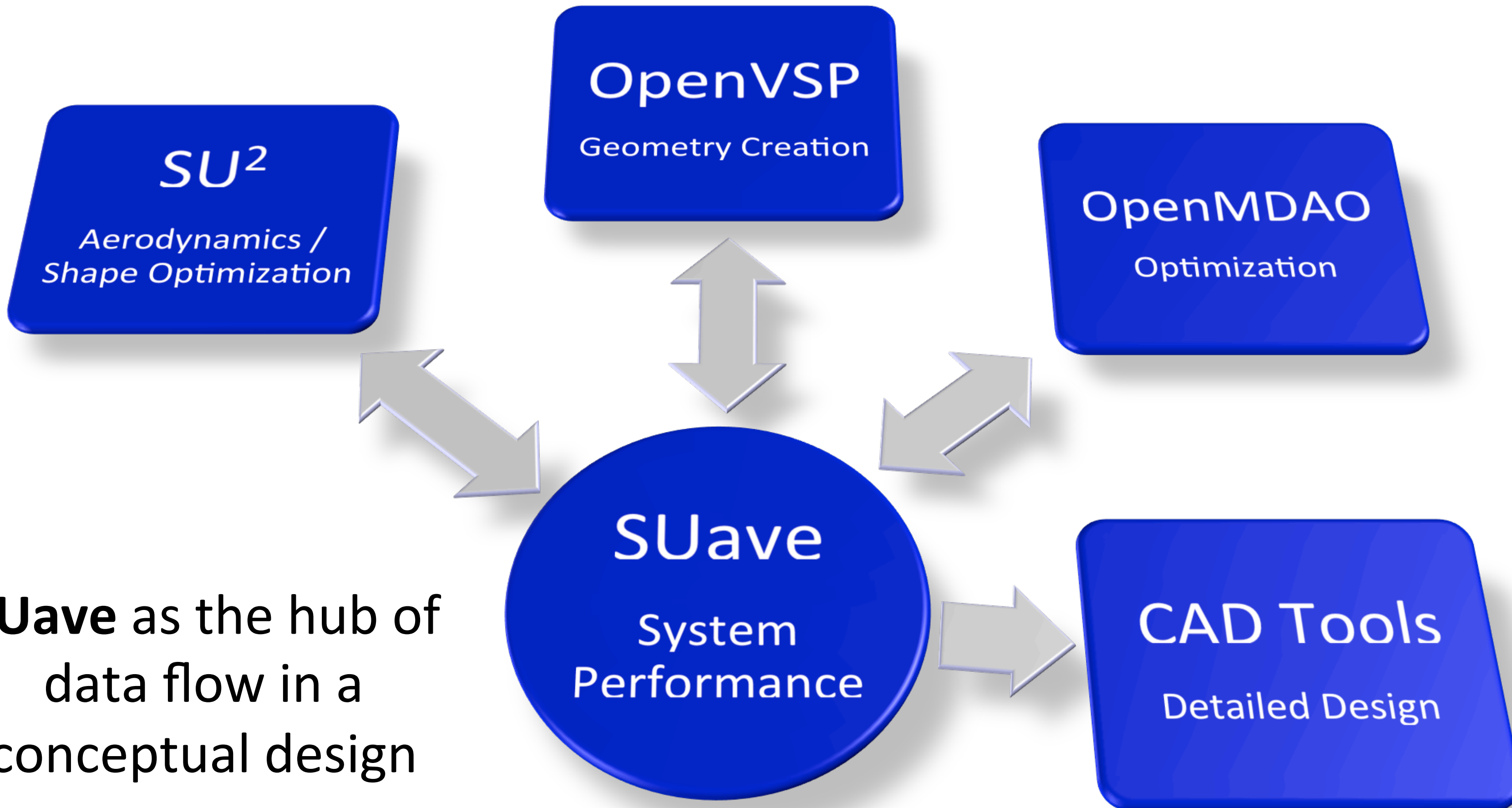
Software Tools

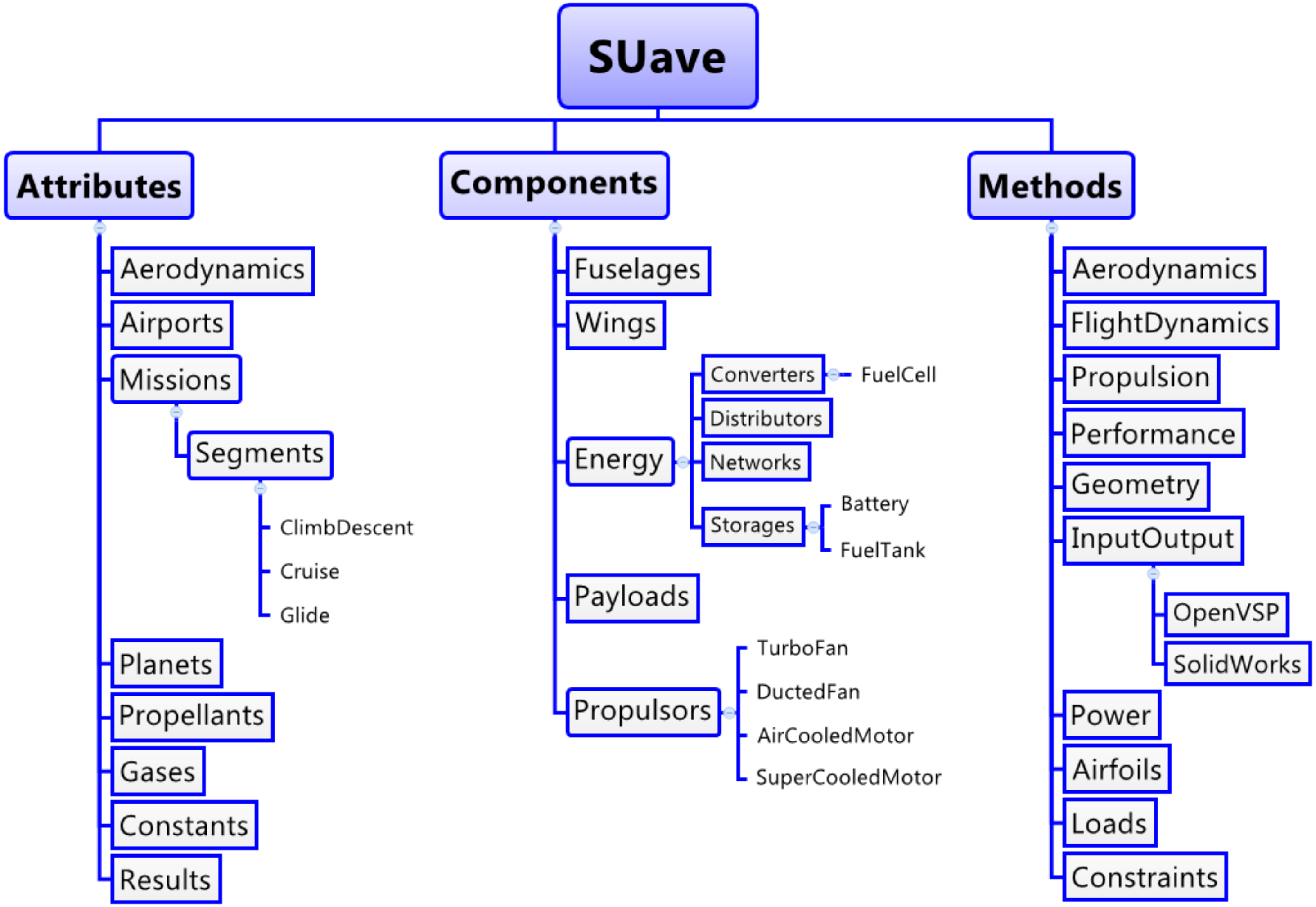


SUave as the hub of data flow in a conceptual design process

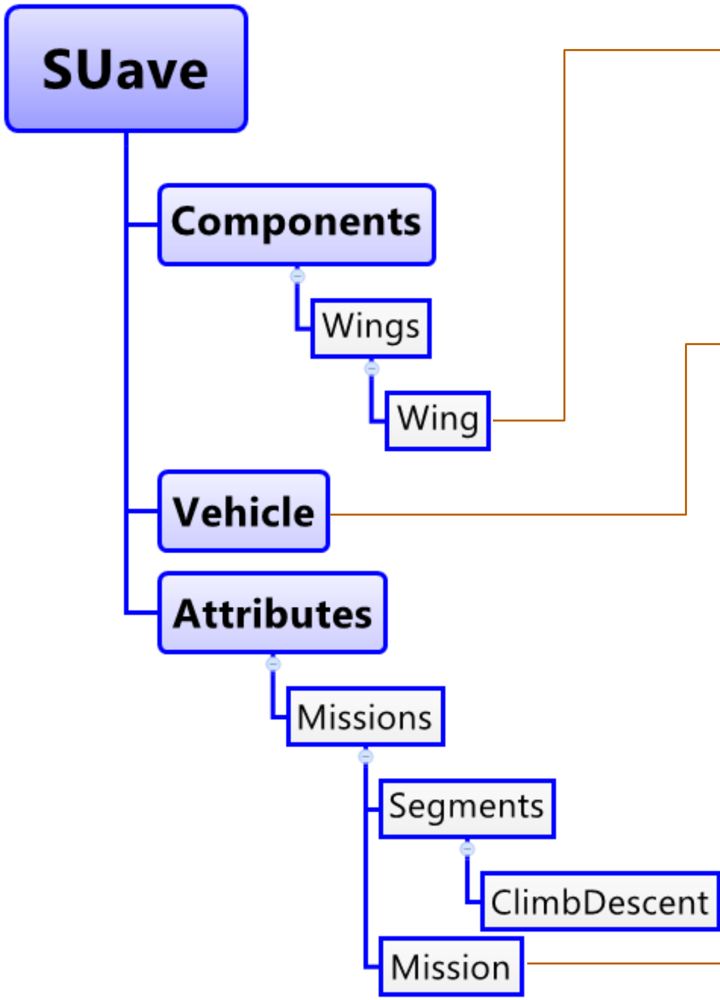
Technical Impacts: Software

- ✓ **SUave** enables rapid conceptual development of arbitrarily complex vehicles
- ✓ Equations of motion are solved directly for each Segment resulting in a Mission history
- ✓ Simulation fidelity is only limited by the fidelity of supporting analyses (aerodynamic performance and mass properties)
- ✓ Easily extensible due to simplicity of architecture and syntax
- ✓ Plugs into existing tool chain via an easily-installable Python module (distutils / Windows installer / RPM / etc.)
- ✓ User's Guide and Technical Reference available online soon: 1.0.0 available by year's end (suave.stanford.edu).

Abbreviated Class Structure



Code Example




```
# Build a Wing
main_wing = Components.Wings.Wing(
    tag = 'Main Wing',
    ref_area     = 1344.0  , #[sq-ft]
    aspect_ratio = 10.19   , #[-]
    # <...>
)

# Assemble a Vehicle
vehicle = SUAVE.Vehicle()
vehicle.add_component(main_wing)
#<...>

# Derive a Configuration
climb_config = vehicle.new_configuration()
config.Wings.Main_Wing.flaps = 'down'

# Plan a Segment
climb = Missions.Segments.ClimbDescent(
    tag = 'Climb',
    altitude   = [0.0, 3.0],  # [km]
    config     = climb_config,
    #<...>
)

# Create a Mission
mission = Missions.Mission()
mission.add_segment(climb)
# <...>
```

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V&V of SUave: B737-800 w/ Winglets

- ✓ As part of an FAA tool comparison project, results for several aircraft conceptual design tools were ran for the B737-800:
  - PASS: Program for Aircraft Synthesis Studies, Stanford Univ
  - EDS: Environmental Design System, Georgia Tech
  - TASOPT: Transport Aircraft System OPTimization, MIT
  - SUave: Stanford University Aerospace Vehicle Environment, Stanford Univ

- ✓ Similar results were obtained with SUave, validating / verifying many of the models included in our new tool

- ✓ SUave is now well positioned to replace our older tools while including the ability to incorporate high fidelity methods, advanced propulsion systems, and better weight estimation methods

V&V of SUave: B737-800 w/ Winglets

Parameter	EDS	PASS	TASOPT (no winglets)	SUave
Cruise Mach	0.78	0.78	0.78	0.78
Mission range (nm)	2,950	2,950	2,950	2,950
R1 range (nm)	2,092.4	2,124	2,230	2,124
Payload (lbs)	36,540	36,540	36,540	36,540
Block fuel (lbs) (mission)	38,180	38,422	41,238	39,556
Beginning cruise altitude (ft)	35,000	35,000	35,000	35,000
Climb fuel burn (lbs)	4,012	4,186	4,522	4,601
Cruise fuel burn (lbs)	32,280	33,160	35,912	32,352
Approach fuel burn (lbs)	1,194	1,076	804	890

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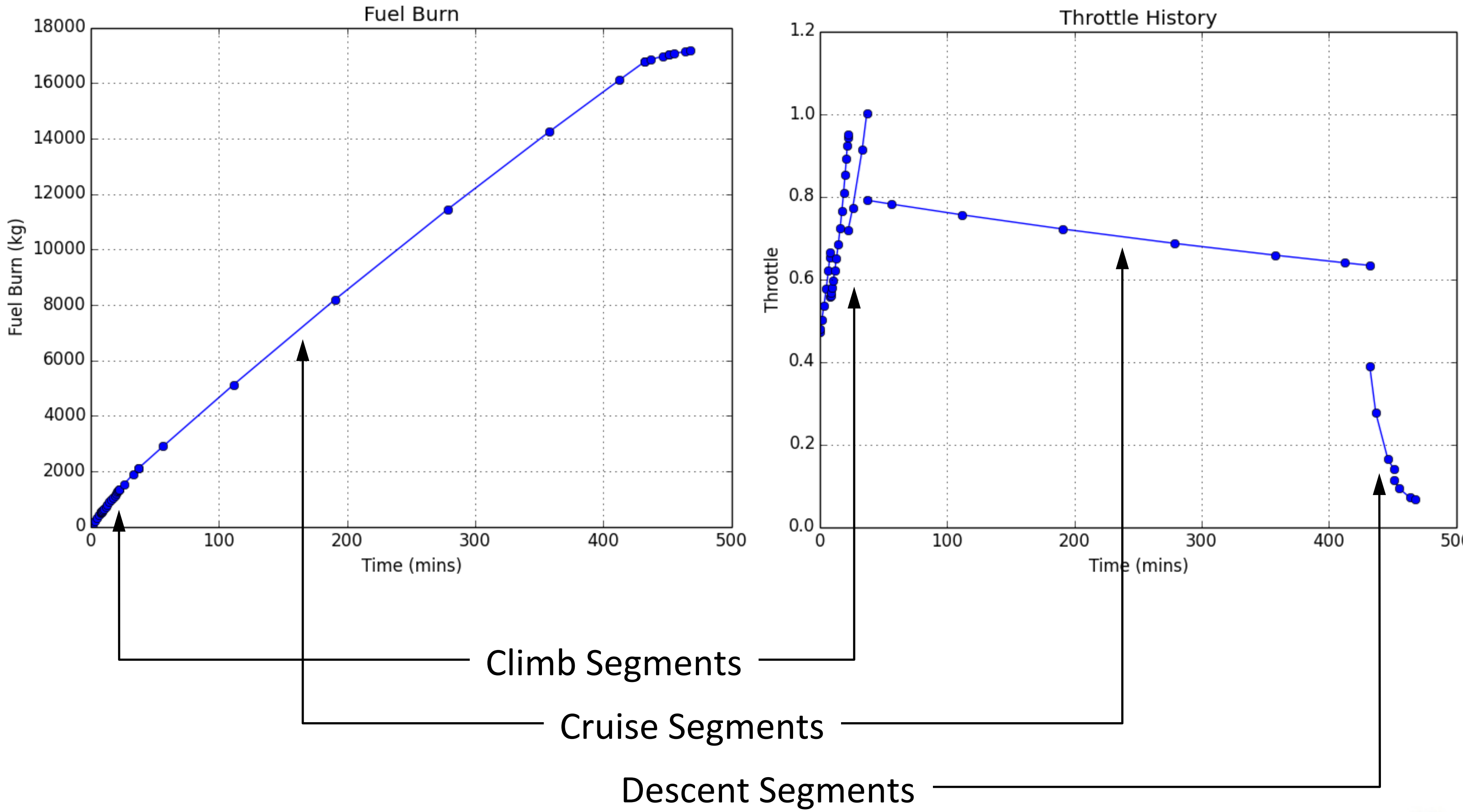
737-800 Validation: Sample Results



Technical Impacts: Concept Aircraft

- ✓ Two carbon-free aircraft concepts evaluated via OpenVSP / **SUave** / SU^2 tool chain:
  - Relatively near-term (present – 5-year timeframe) power, propulsion, and material technologies
  - High-fidelity aerodynamic properties via automatic mesh generation (Salome) / SU^2 (Euler solutions; drag polars with AoA and sideslip angle)
  - Collaboration with corporate partners for relevant technology data (American Superconductor & IBM)
- ✓ Structural mass estimated from 737-800 data, correlations, and recent trends (more research will needed here: planning FEM-based weight estimation capability, see Gern 2012)
- ✓ Internal layout (fuel storage, seating, etc.) via SolidWorks (exported from SUave through API)

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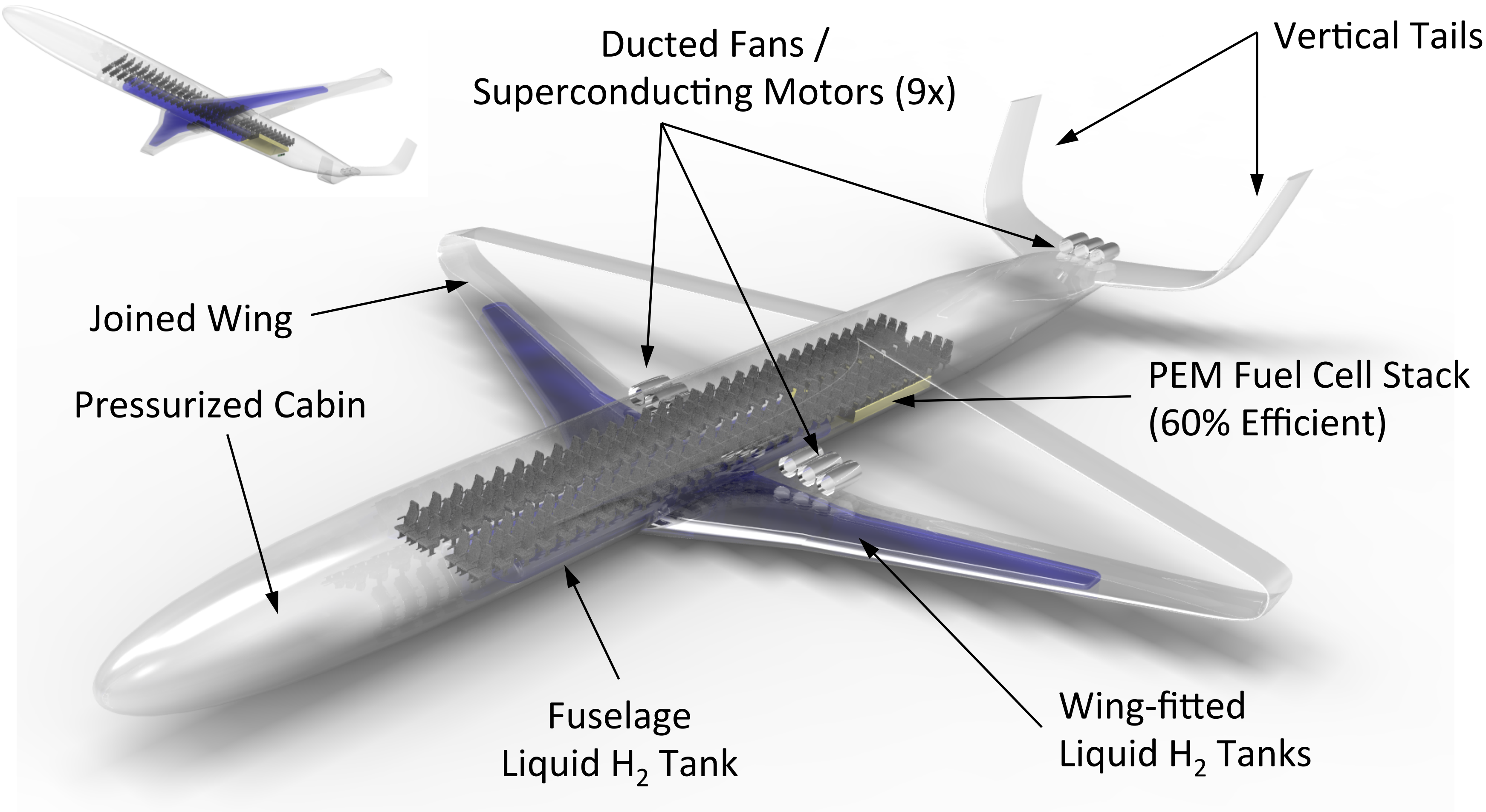
Technical Impacts: Concept Aircraft

- ✓ Replacement carbon-free aircraft for Boeing 737-800
- ✓ Assume that baseline range and cruise speed are operational constraints
- ✓ Seating for 180 passengers with same cargo capacity
- ✓ Two concept aircraft presented:
  - Liquid H_2 / fuel cells / superconducting motor combination
  - Propulsion via ducted fans (several small "engines" used for BLI opportunity)
  - Additional lift/drag from shape design
  - Additional volume required to accommodate low-density H_2 fuel
  - Fuel tank is a significant source of additional mass

Concept Aircraft 1



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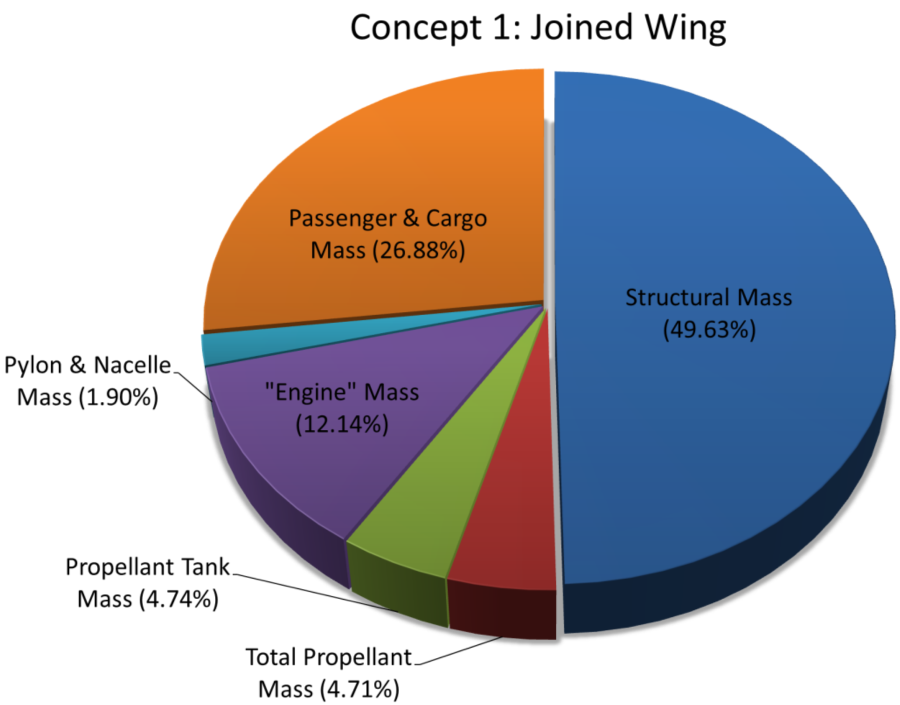
Concept Aircraft 1

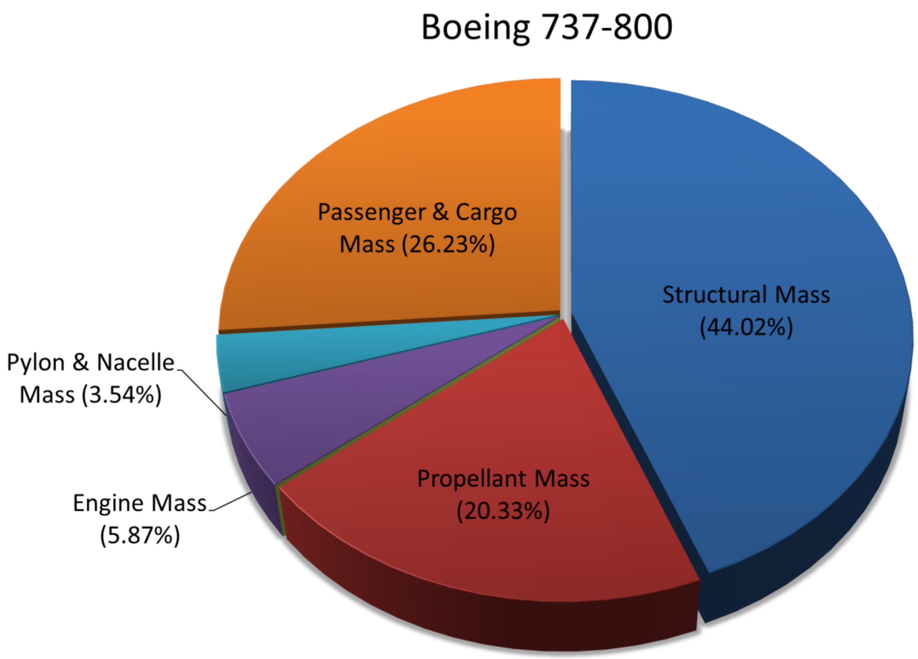


Empty Mass: 53,909 kg

Maximum Liftoff Mass: 78,800 kg

Empty Mass: 41,413kg

Maximum Liftoff Mass: 79,010 kg



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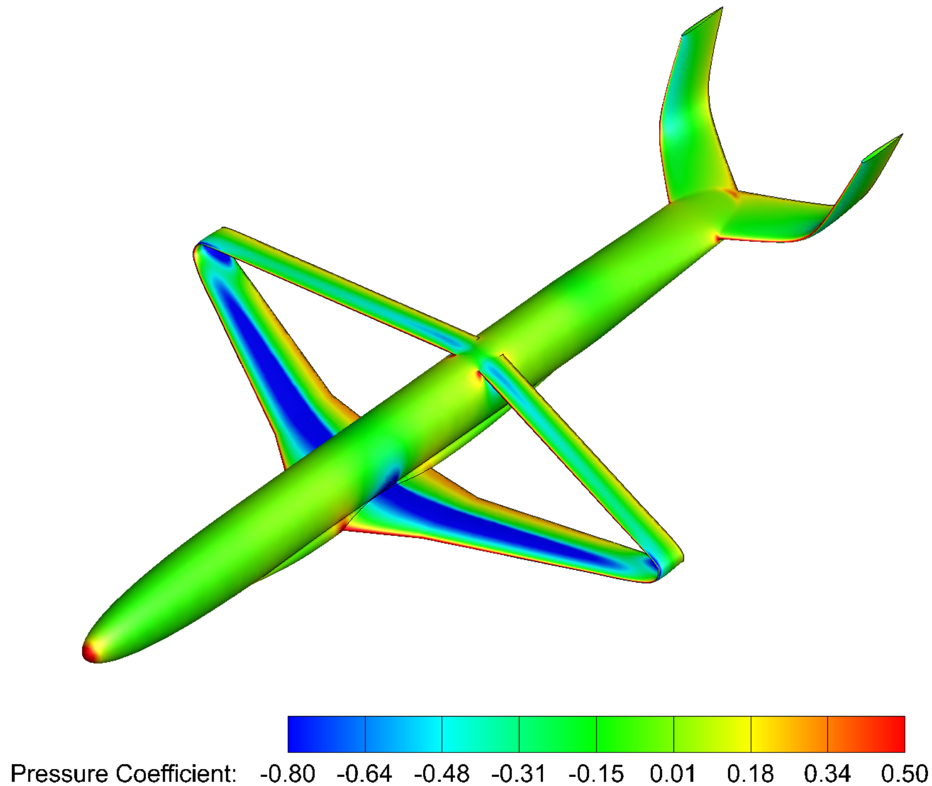
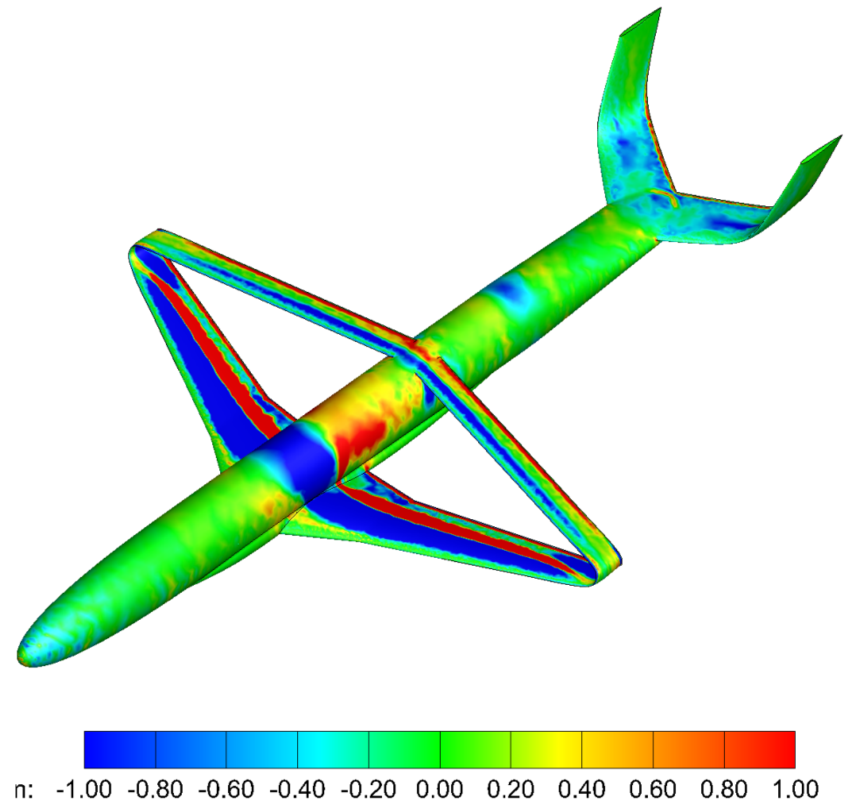
Concept Aircraft 1



Pressure Coefficient Distribution (SU^2 CFD Calculations integrated into SUave)

Shape Sensitivity (SU^2: Adjoint L/D)



Surface shape sensitivities can be incorporated into optimization wrapper around SUave. Enables multi-fidelity optimization

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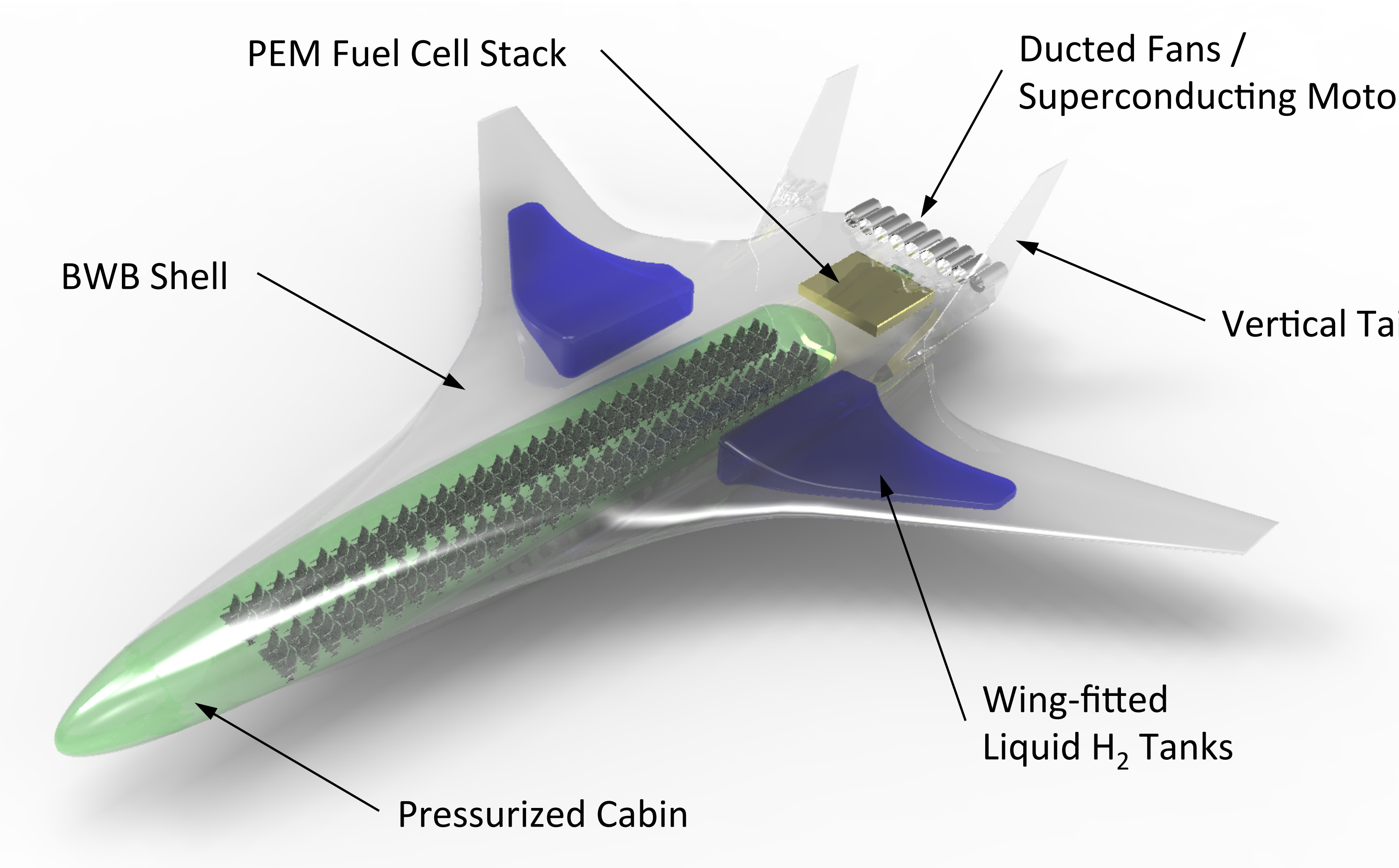
Concept Aircraft 2



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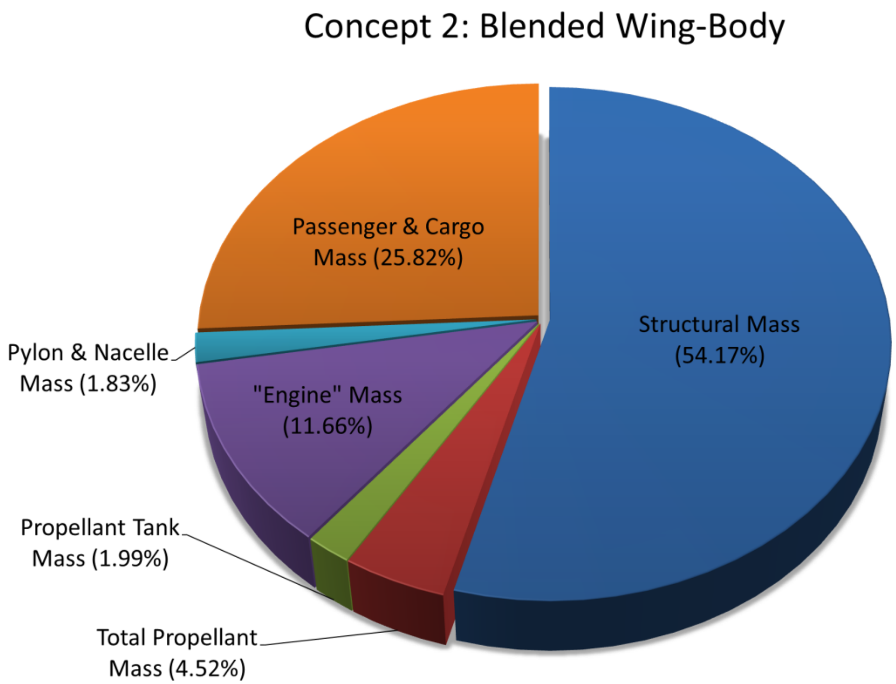
Concept Aircraft 2

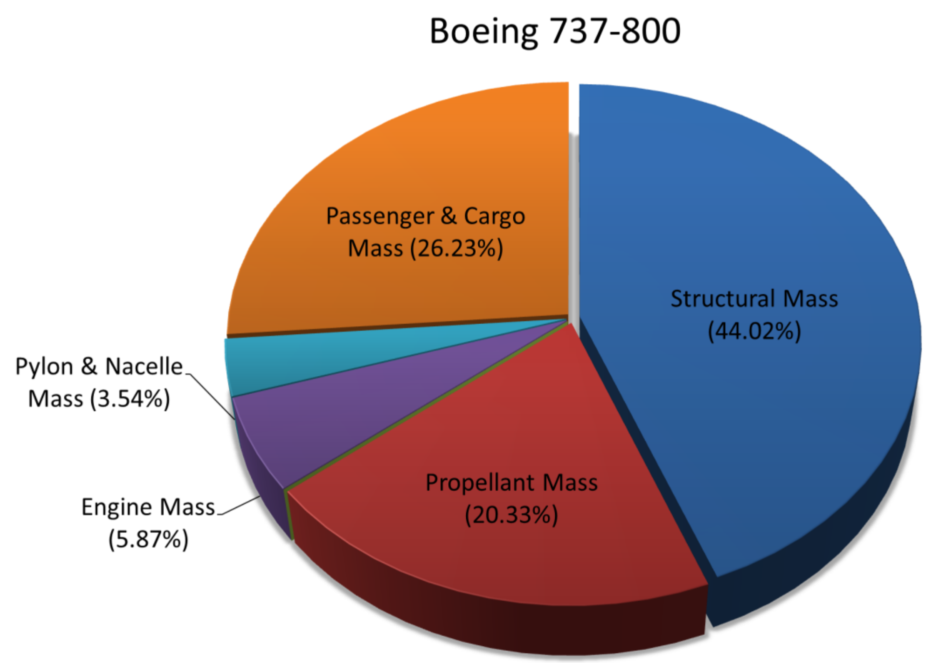


Empty Mass: 57,139 kg

Maximum Liftoff Mass: 82,029 kg

Empty Mass: 41,413kg

Maximum Liftoff Mass: 79,010 kg



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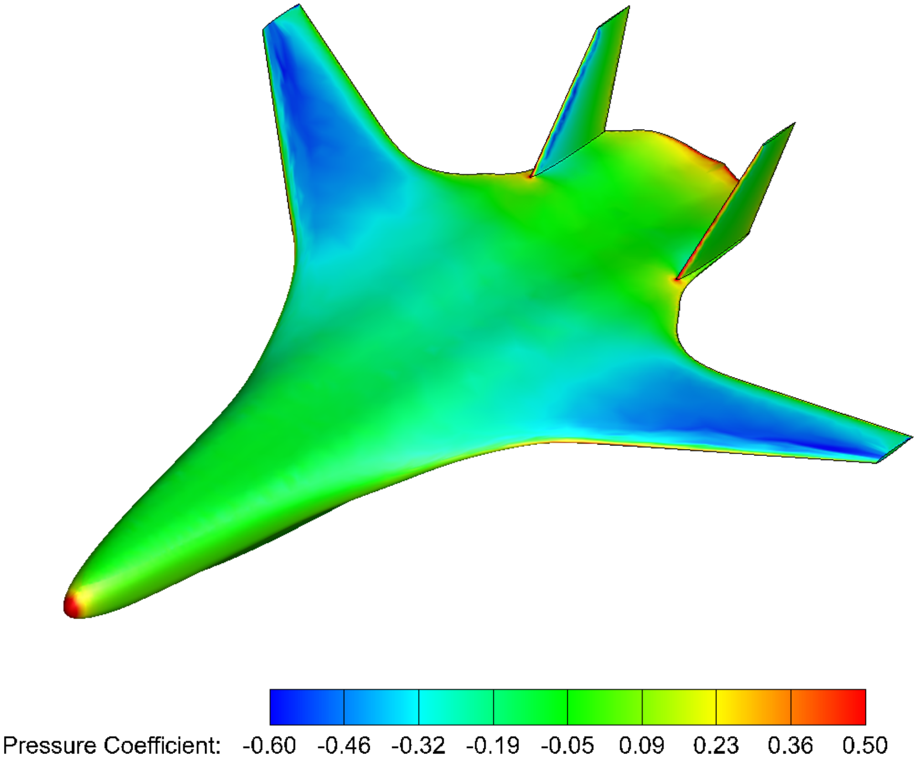
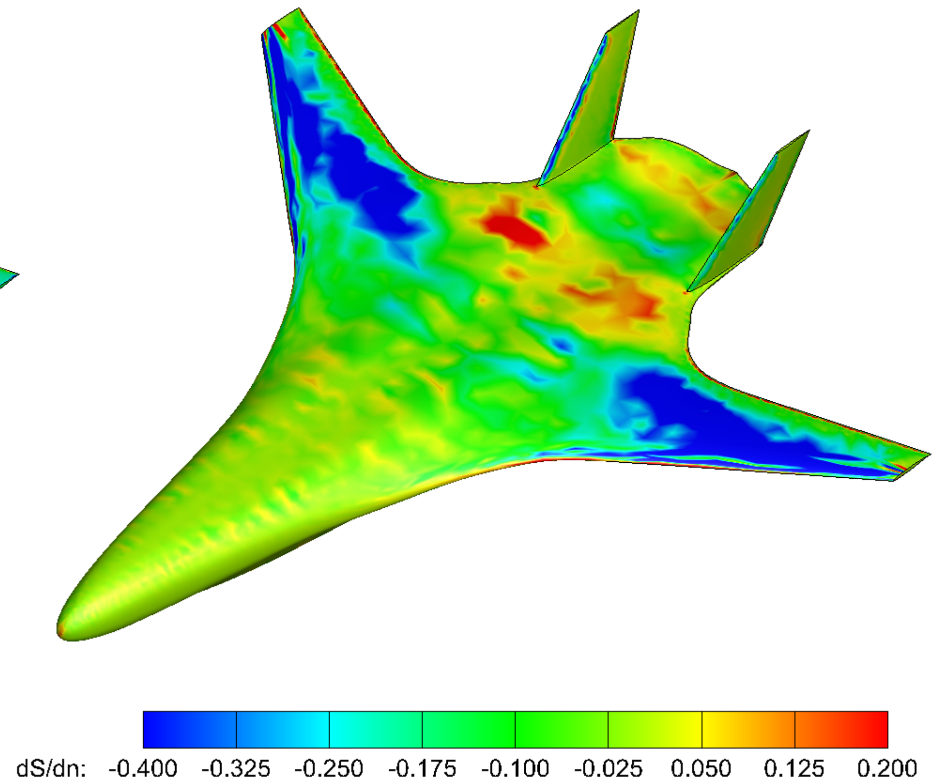
Concept Aircraft 2



Pressure Coefficient Distribution
(SU^2: Flow)

Shape Sensitivity (SU^2: Adjoint L/D)



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Summary of Phase 1 Efforts

- ✓ Created **SUave** software tool for “next gen” aerospace vehicle development; public distribution shortly
- ✓ Validated **SUave** against known existing aircraft performance data (Cessna 172R Skyhawk and Boeing 737-800)
- ✓ Comprehensive review of energy storage and propulsion technologies available to near-future aircraft (with partners)
- ✓ Created models of advanced propulsion methods for carbon-free aviation
- ✓ Developed two candidate carbon-free 737-800 replacement aircraft using the OpenVSP-SUave-CAD tool chain
- ✓ Software framework laid for complete integration with OpenMDAO, bi-directional OpenVSP integration, and export to commercial CAD

Distribution & Dissemination

- ✓ **SUave** (version 1.0.0) to be published as open-source Python module (all platforms) - end of 2013
  - Distutils installation for any platform (`setup.py`…)
  - Executable installers for Windows (.msi) / Linux (RPM) / Mac
  - Online / PDF documentation (hosted at Stanford)
  - Community contributions encouraged
  - Integration into aircraft design courses (hopeful)

- ✓ Publications planned:
  - An Introduction to SUave (conference paper and workshop)
  - High-fidelity optimizations of the carbon-free 737-800 replacement concepts via SUave – SU^2 (journal paper)

Future Work

- ✓ Four key areas identified in Phase I work which need more attention to achieve SUave's goals:
  1. Structural mass estimation based on physics & engineering (FEA), not correlations of existing aircraft
  2. "Medium-fidelity" aerodynamic analysis (vortex-lattice, full potential) for initial design
  3. Ability to include aero-elastic constraints in sizing / optimization loop
  4. Robust surface and volume meshing for SU^2 (or other external CFD, e.g. FUN3D)
  5. A platform-independent user interface (visualize 3D geometry, view aerodynamic results, etc.)

- ✓ These are areas of primary focus for Phase II…

Questions & Answers

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Future Work

✓ **SUave** development will continue with many enhancements and new features planned:

- Expanded catalogue of Mission Segments, including launch vehicle trajectories and SSTO missions
- Expanded catalogue of Propulsors, including rockets and hybridized electric / jet models
- Assimilate SPOT (Stanford Program for Optimal Trajectories) in SUave to support launch vehicle / missile vehicles
- Tighter SU^2 integration to embed high-fidelity aerodynamics into SUave
- Tighter OpenMDAO integration allowing for SUave-based optimizations
- Bi-directional OpenVSP integration (currently import only)
- Expanded CAD export support (currently SolidWorks supported)
- Lower-fidelity aerodynamic performance tools for rapid prototyping (integrated vortex lattice, panel, and full-potential solvers)
- Better multi-threading for running numerous Vehicle / Mission simulations